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PRESSURE AND HEAT-TRANSFER MEASUREMENTS ON A SLOTTED LEADING EDGE IN HYPERSONIC FLOW

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14 APR 1972

C. G. Burchfield and P. J. Bontrager
ARO, Inc.

May 1966

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PRESSURE AND HEAT-TRANSFER MEASUREMENTS ON A SLOTTED LEADING EDGE IN HYPERSONIC FLOW

C. G. Burchfield and P. J. Bontrager
ARO, Inc.

FOREWORD

The work reported herein was done at the request of the Air Force Flight Dynamics Laboratory (AFFDL), Air Force Systems Command (AFSC) under Program Element 62405334, Project 1366, and Task 136607.

Test results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The tests were conducted during the period from July 22, 1965 through March 3, 1966 under ARO Project No. VT0616. The manuscript was submitted for publication on April 15, 1966.

This technical report has been reviewed and is approved.

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ABSTRACT

Pressure and heat-transfer tests were conducted using a highly swept cylindrical leading-edge model. The effects of slots and slot geometry were investigated. Slots were varied in width and depth from 0 to 0.50 in., and the leading-edge sweep angle was varied from 45 to 90 deg. The tests were conducted at nominal Mach numbers of 6, 8, and 10. Pressure data were obtained at a free-stream Reynolds number of 1.0 million/ft, and heat-transfer data were obtained at 1.0 and 2.0 million/ft. Selected results are presented to show the effect of the slots upon the leading-edge pressure and heat-transfer distributions.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

b	Model skin thickness, ft
C_p	Pressure coefficient, $(p - p_\infty)/q_\infty$
c	Specific heat of model material, Btu/lb-°R
d	Slot depth, in.
h	Local heat-transfer coefficient on model, Btu/ft^2-sec-°R
h_T	Heat-transfer coefficient based on $\dot{q}_o(I)$, Btu/ft^2-sec-°R
M_∞	Free-stream Mach number
p	Local pressure on model, psia
p_o	Tunnel stagnation pressure, psia
p_∞	Free-stream static pressure, psia
q_∞	Free-stream dynamic pressure, psia
$\dot{q}$	Local heat-transfer rate on model, Btu/ft^2-sec
$\dot{q}_o$	Fay and Riddell stagnation heat-transfer rate on 2-in.-diam hemisphere, Btu/ft^2-sec
$\dot{q}_o(I)$	Inferred stagnation heat-transfer rate on unswept 2-in.-diam cylindrical leading edge, Btu/ft^2-sec
R_o	Radius of the hemisphere, 1.0 in.
R_T	Radius of the cylindrical leading edge, 1.0 in.
Re_∞	Free-stream Reynolds number
T_o	Tunnel stagnation temperature, °R
T_w	Model wall temperature, °R
t	Time, sec
W	Slot width, in.
w	Density of model material, lb/ft^3
x	Model surface distance, in.
Λ	Sweep angle, deg

SECTION I
INTRODUCTION

Pressure and heat-transfer tests have been conducted on a swept, cylindrical leading edge. The primary purpose of the tests was to determine the effects of slots and slot geometry. Slot width and depth were varied from 0 to 0.5 in. Measurements were made at sweep angles from 45 to 90 deg at nominal Mach numbers of 6, 8, and 10. The pressure tests were conducted at free-stream Reynolds numbers of 1.0 million/ft and the heat-transfer tests at 1.0 and 2.0 million/ft. The tests were performed in the 50-in. hypersonic tunnels (Gas Dynamic Wind Tunnels, Hypersonic (B) and (C)) of the von Kármán Gas Dynamics Facility (VKF).

SECTION II
APPARATUS

2.1 MODELS

Two 1-in.-radius leading-edge models (Fig. 1) were supplied by AFFDL. Each model consisted of a movable and a fixed section. The movable section was free to slide in both spanwise and chordwise directions with respect to the fixed section. By adjusting the movable section and inserting ceramic blocks, slot depths and widths from 0 to 0.50 in. could be obtained. Also, by adjusting the movable section in the chordwise direction only, backward facing steps from 0 to 0.5 in. high were obtained. A limited amount of data was obtained on these configurations. Variation of the leading-edge sweep angle was accomplished by using the tunnel pitch mechanism and bent stings.

The pressure model was instrumented with 99 pressure orifices and the heat-transfer model with 98 Chromel®-Alumel® thermocouples. The heat-transfer model skin was made of type 321 stainless steel approximately 0.05 in. thick. Instrumentation was located along the leading edge on the stagnation line, on rays 15, 30, 45, 75, and 90 deg from the stagnation line, and on the faces of the slot.

2.2 WIND TUNNELS

Tunnels B and C are 50-in.-diam, continuous flow, closed-circuit, variable density wind tunnels equipped with axisymmetric, contoured nozzles. Tunnel B operates at nominal Mach numbers of 6 and 8 at stagnation pressures from 20 to 280 psia and 50 to 900 psia, respectively. Tunnel C operates at a nominal Mach number of 10 at stagnation pressures of 200 to 2000 psia. Stagnation temperatures up to 1350°R in Tunnel B and 1900°R in Tunnel C are utilized to prevent liquefaction of the air in the test section.

Tunnel C and its associated equipment are shown in Fig. 2. As shown in this figure, the model may be injected into the tunnel for a test run and then retracted into the test section tank for cooling of the model or for making model changes without interrupting the tunnel airflow. Details of Tunnel B are similar to those of Tunnel C. A more complete description of the tunnels may be found in Ref. 1.

2.3 INSTRUMENTATION

Pressures were measured using the standard pressure systems of Tunnels B and C. The Tunnel B system utilizes one 15-psid frequency-modulated transducer per channel. Each channel in the Tunnel C system includes two frequency-modulated transducers, a 1-psid unit and a 15-psid unit, which are switched in and out of the system automatically to allow measuring to the best precision. From static calibrations, the precision of measurement for Tunnel B is estimated to be ±0.003 psia or ±1 percent, whichever is larger. For Tunnel C, the estimated precision is ±0.001 psia or ±1 percent, whichever is larger.

During the heat-transfer tests, the reference junction of each thermocouple was maintained at 592°R. The thermocouple outputs were recorded in digital form on magnetic tape at a rate of 20 times/sec. The estimated precision of the temperature systems is ±2°R.

Schlieren photographs of the model flow field were obtained during all tests. A typical photograph at Mach 10 is shown in Fig. 3.

SECTION III
PROCEDURE

3.1 TEST PROCEDURE

The conditions at which tests were conducted are as follows:

M_∞	p_o, psia	T_o, °R	$Re_\infty \times 10^{-6}$, ft^{-1}
5.99	55	850	1.0
7.92	200	1240	1.0
10.08	750	1800	1.0
6.02	110	850	2.0
7.97	425	1290	2.0
10.17	1650	1890	2.0

Transient heat-transfer data were obtained by injecting the model into the airstream for a specified period of time while model thermocouple histories were recorded. The model was then retracted into the installation chamber below the tunnel and cooled with air. This procedure was repeated at all conditions.

3.2 DATA REDUCTION

Test information was processed with an IBM 7074 computer. The heating rate was calculated from the equation

$$\dot{q} = wbc \frac{dT_w}{dt}$$

and heat-transfer coefficients from

$$h = \frac{\dot{q}}{T_o - T_w}$$

A least-squares polynomial was fit to a series of 21 consecutive temperatures taken at 0.05-sec intervals, where zero time was considered as the time at which the model reached the centerline of the tunnel. The polynomial and its derivative were used to determine the heating rate and the heat-transfer coefficients. For the data presented in this report, dT_W/dt was evaluated at 0.5 sec.

For analysis and comparison the measured heat-transfer data were referenced to a theoretical stagnation heat-transfer coefficient on an unswept cylinder. The reference heat-transfer rate was inferred from the theoretical stagnation point heat-transfer rate on a 2-in.-diam hemisphere by the following equation:

$$\dot{q}_o(I) = \frac{0.729\, \dot{q}_o \sqrt{R_o}}{\sqrt{R_T}} = 0.729\, \dot{q}_o$$

where q_o was obtained by the method of Ref. 2, and the constant 0.729 was obtained from Ref. 3, p. 300, Eq. (8.3.20). The reference heat-transfer coefficient, h_T, was calculated as follows:

$$h_T = \frac{\dot{q}_o(I)}{T_o - T_w}$$

Tunnel free-stream conditions at Mach 6 and 8 were computed assuming isentropic expansion of a perfect gas. Free-stream conditions at Mach 10 were computed assuming isentropic expansion of a Beattie-Bridgeman gas with variable specific heats, following the methods of Ref. 4.

SECTION IV
RESULTS AND DISCUSSION

Pressure and heat transfer on a yawed, cylindrical leading edge having a slot were investigated, and the results from tests at Mach 10 are presented in Figs. 4 and 5. Data at sweep angles of 45 and 75 deg are shown for comparison. In these figures it is apparent that the predominant influence is the presence of the slot rather than slot geometry. Upstream, the slot has negligible effect on pressure, whereas a definite decrease in heat transfer is observed near the slot. Immediately downstream of the slot, pressure and heat transfer are increased by the presence of the slot. The effects of slot geometry are small and are limited to a distance of approximately 0.50 in. downstream of the slot. In this region pressure and heat transfer tend to increase slightly with increasing slot width (Fig. 4).

As shown in Fig. 5, pressures along the leading edge are independent of slot depth. The heat-transfer data, however, show a small effect of slot depth. For a sweep angle of 45 deg, heat transfer immediately downstream of the slot decreases slightly as depth is increased. As sweep angle is increased to 75 deg this trend reverses. Similar trends were observed at Mach 6 and 8; therefore these data are not shown.

To investigate the effect of Reynolds number on the behavior of slots, heat-transfer data were obtained at Reynolds numbers of 1.0 and 2.0 million/ft. From the data presented in Fig. 6, it appears that the effects of the slot on heat transfer are relatively independent of Reynolds number.

The influence of Mach number on leading-edge pressure and heat transfer is shown in Fig. 7. In addition to the expected increase in the level of pressure and heat transfer with Mach number, the heat-transfer data also show that higher heating rates occur as a result of the slot sensitivity to increasing Mach number. Although small, this increase in heat transfer is of the same order of magnitude as obtained by increasing slot width, at 45-deg sweep, as shown in Fig. 4. The distance from the slot downstream over which the Mach number effect is evident is about 1.0 in., as compared to 0.50 in. for increasing slot width.

SECTION V
CONCLUSIONS

Pressure and heat-transfer tests have been conducted on a swept, cylindrical leading edge. Measurements were made at Mach numbers 6, 8, and 10, and slot depth and width were varied from 0 to 0.5 in. Heat-transfer data were obtained at Reynolds numbers of 1.0 and 2.0 million/ft. The effects of these parameters are summarized as follows:

1. The effects of slot geometry were small in comparison to the influence of the presence of the slot,
2. Slot geometry effects were evident only within 0.50 in. of the slot,
3. Changing Reynolds number from 1.0 to 2.0 million/ft at Mach 10 has a negligible effect on the slot, and
4. Mach number effect was small and limited to about 1.0 in. downstream of the slot.

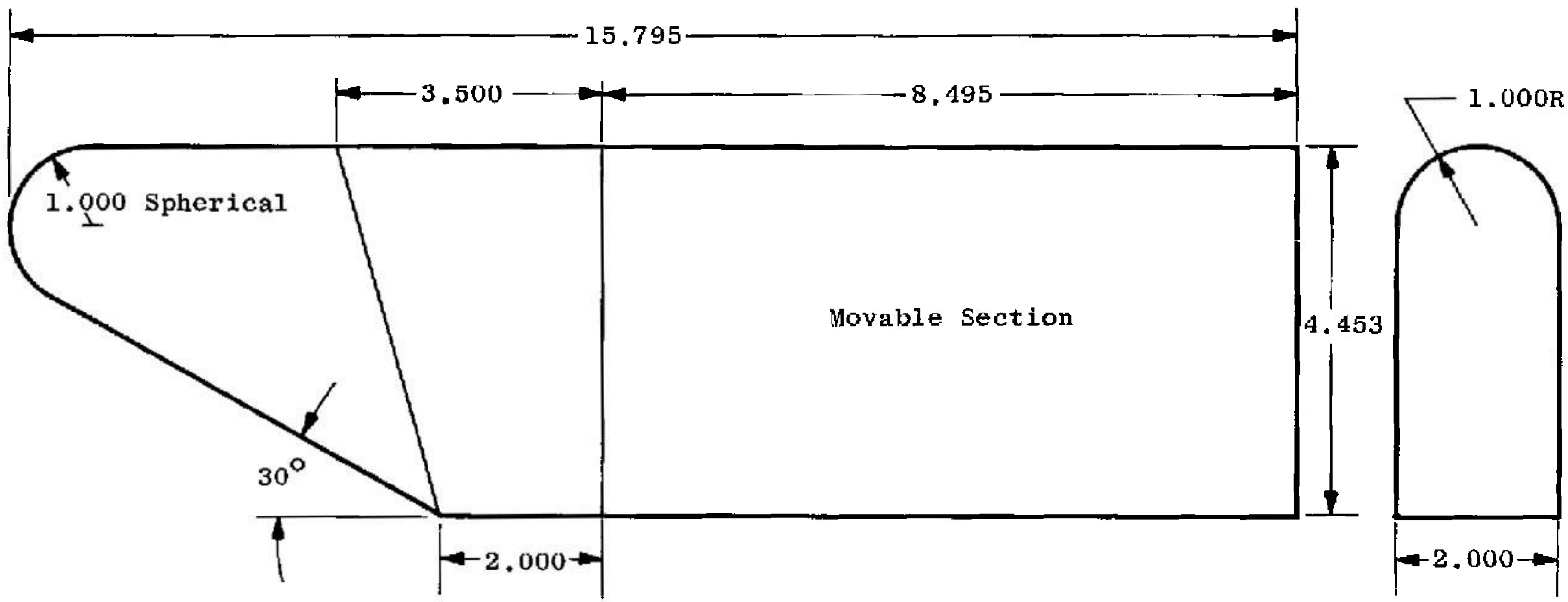
REFERENCES

1. Test Facilities Handbook (5th Edition). "von Kármán Gas Dynamics Facility, Vol. 4." Arnold Engineering Development Center, July 1963.

2. Fay, J. A. and Riddell, F. R. "Theory of Stagnation Point Heat Transfer in Dissociated Air." Journal of the Aeronautical Sciences, Vol. 25, February 1958, pp. 73-85.

3. Hayes, W. D. and Probstein, R. F. Hypersonic Flow Theory. Academic Press, New York, 1959.

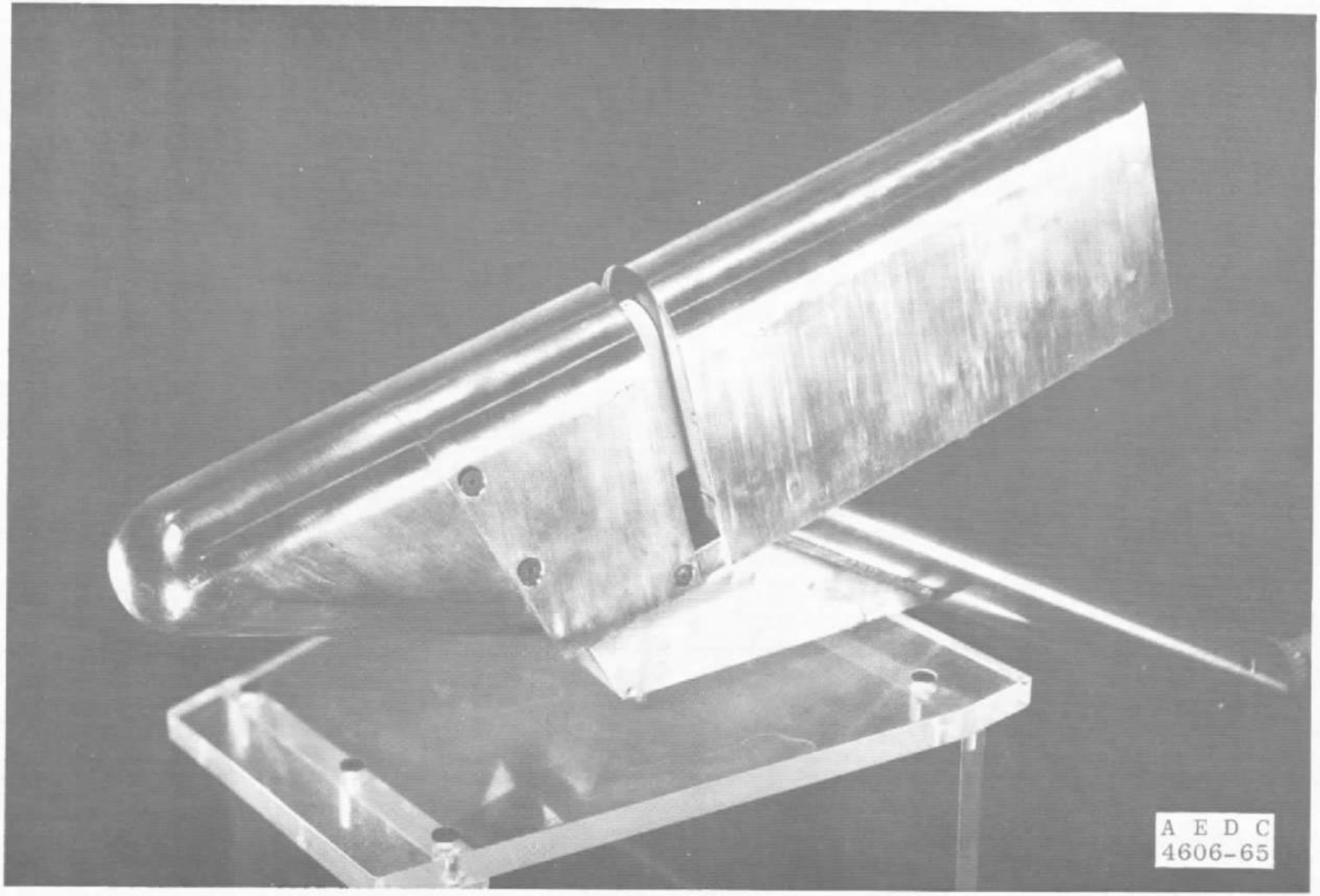
4. Randall, R. E. "Thermodynamic Properties of Air: Tables and Graphs Derived from the Beattie-Bridgeman Equation of State Assuming Variable Specific Heats." AEDC-TR-57-8 (AD135331), August 1957.



All Dimensions in Inches

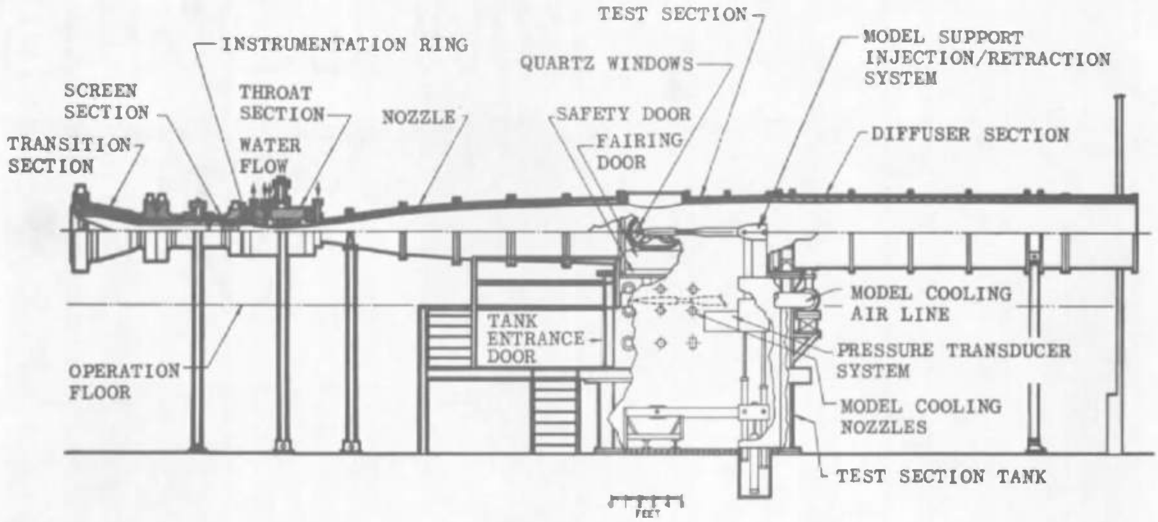
a. Model Details

Fig. 1 Test Model

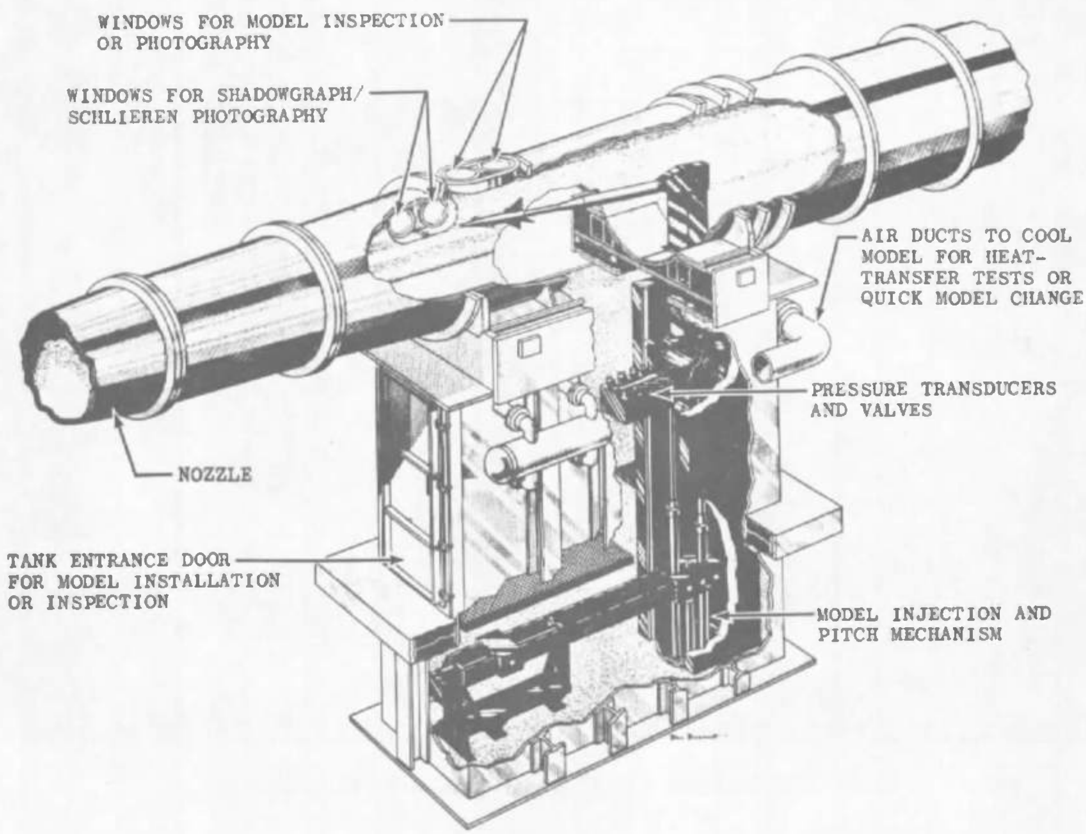


b. Photograph of the Heat-Transfer Model with 0.50-in.-wide Slot

Fig. 1 Concluded



Tunnel Assembly



Tunnel Test Section

Fig. 2 Tunnel C

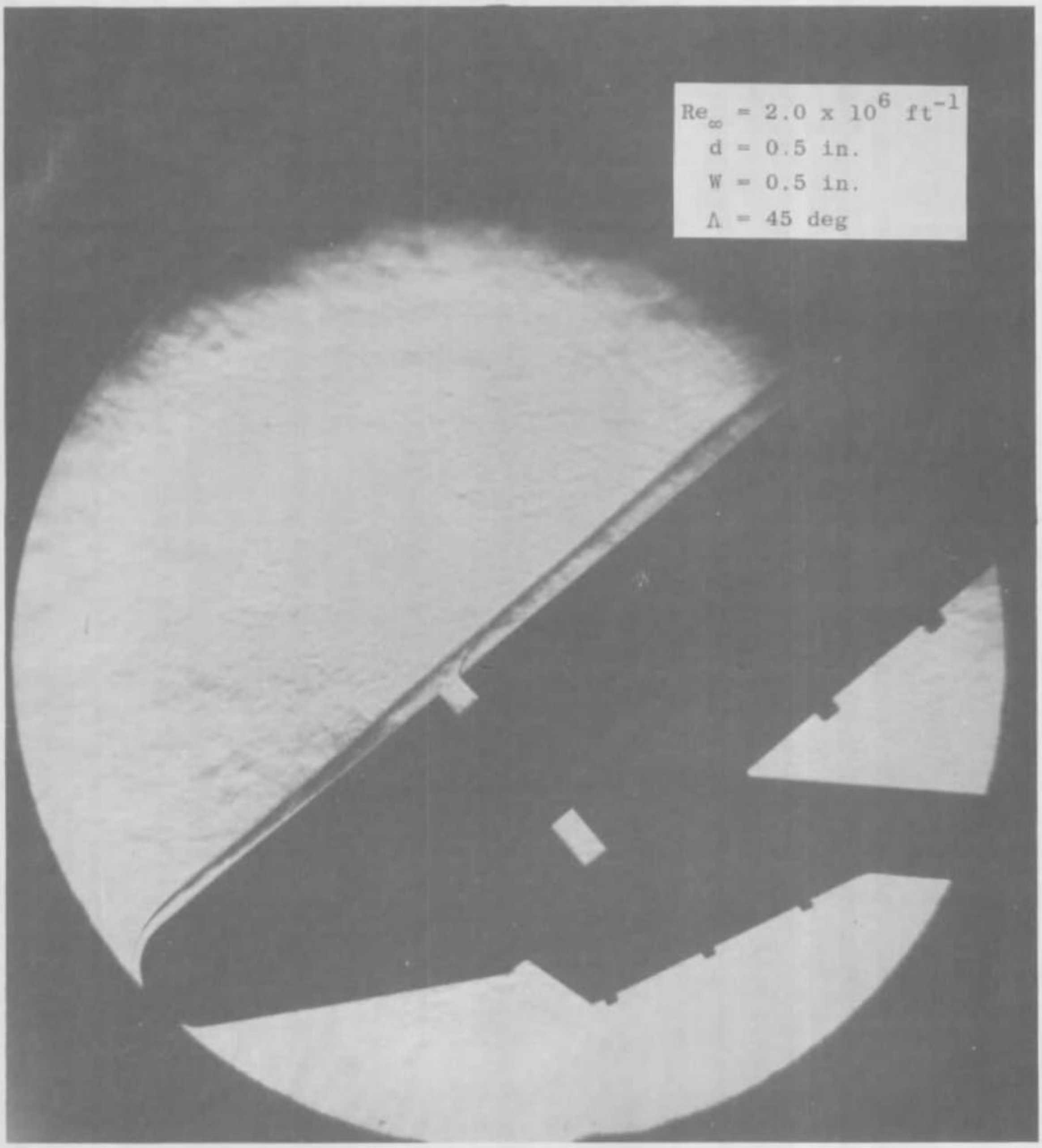


Fig. 3 Typical Schlieren Photograph at Mach 10

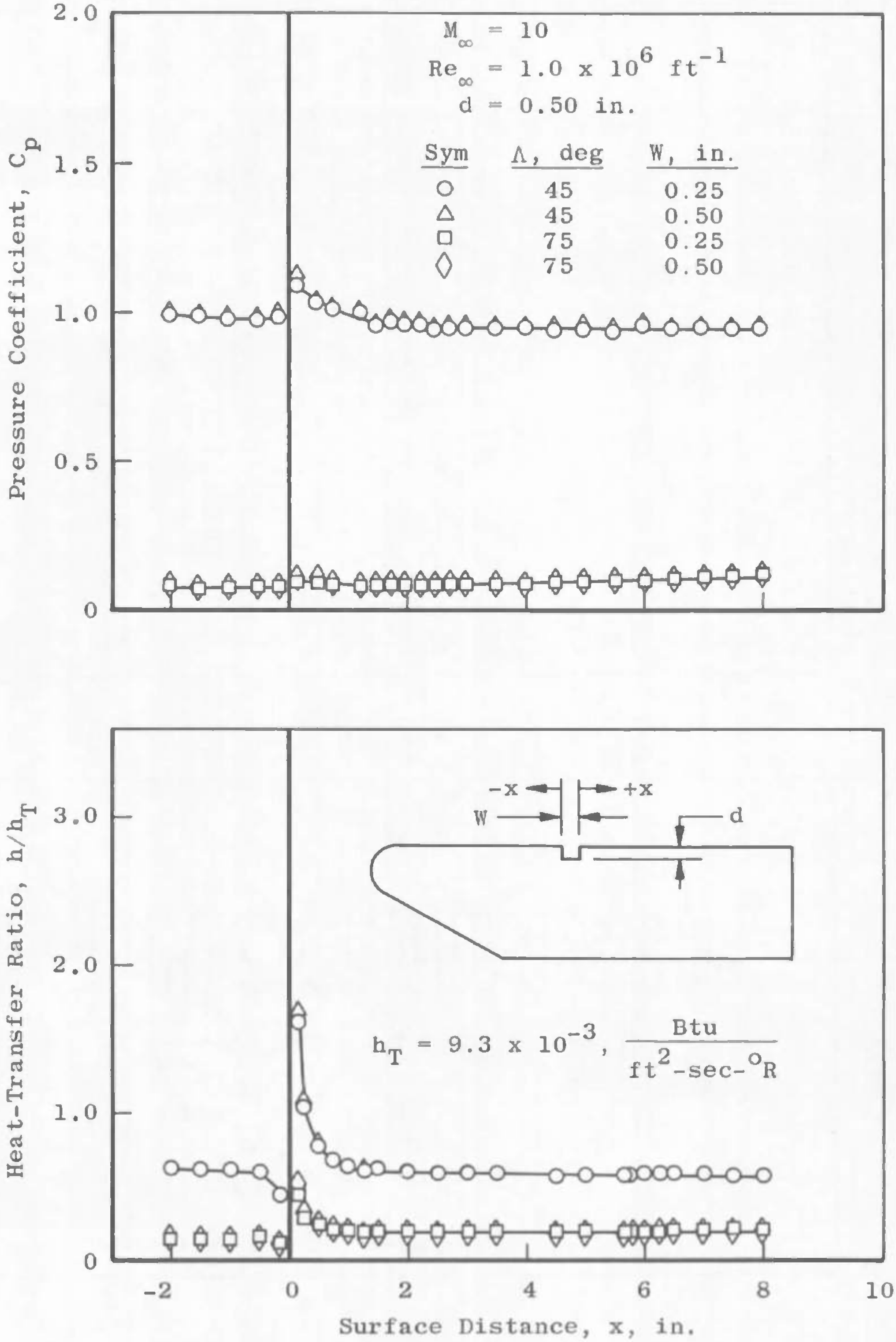


Fig. 4 Effect of Slot Width on Leading-Edge Pressure and Heat-Transfer Distributions at Mach 10

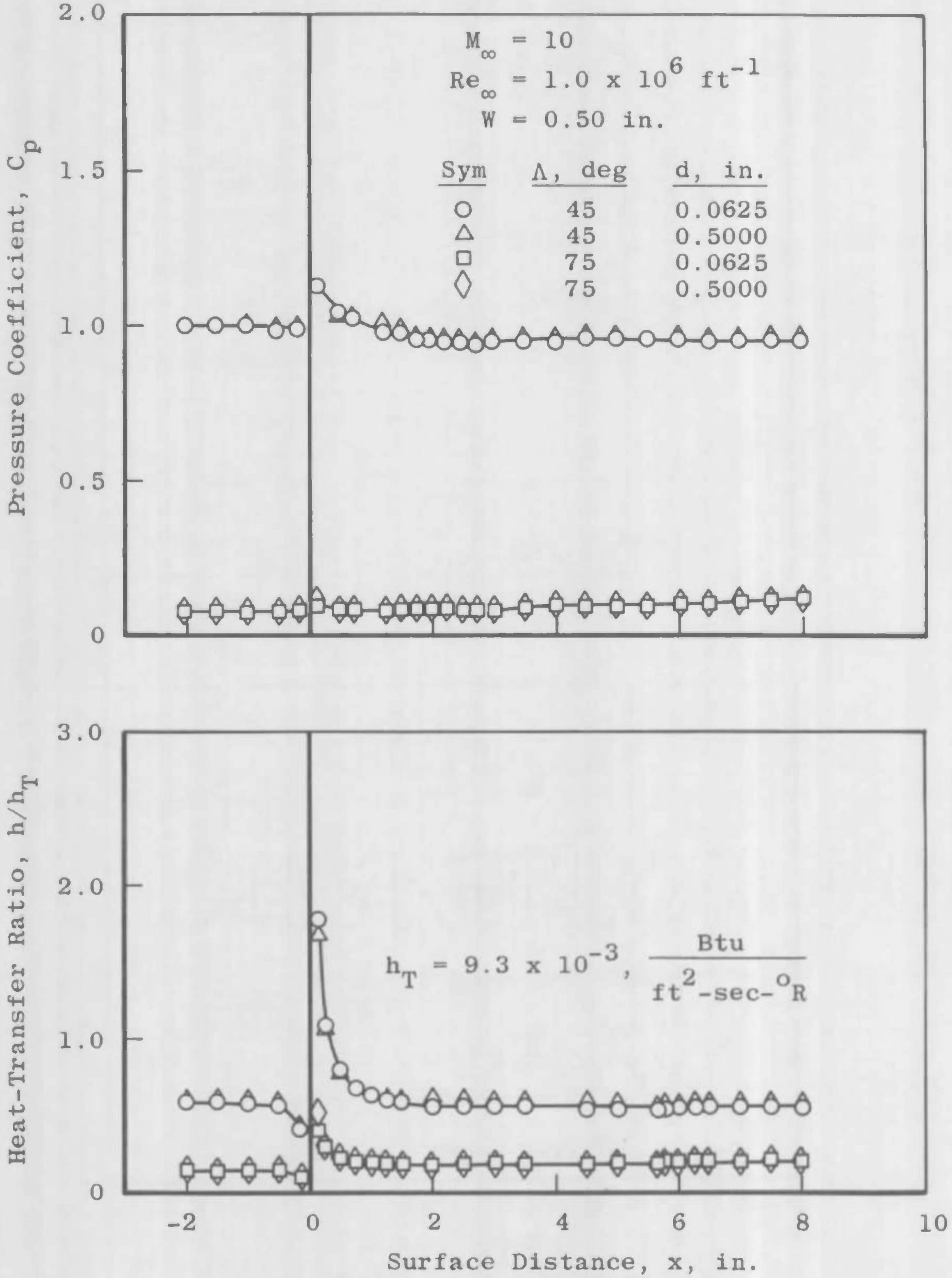


Fig. 5 Effect of Slot Depth on Leading-Edge Pressure and Heat-Transfer Distributions at Mach 10

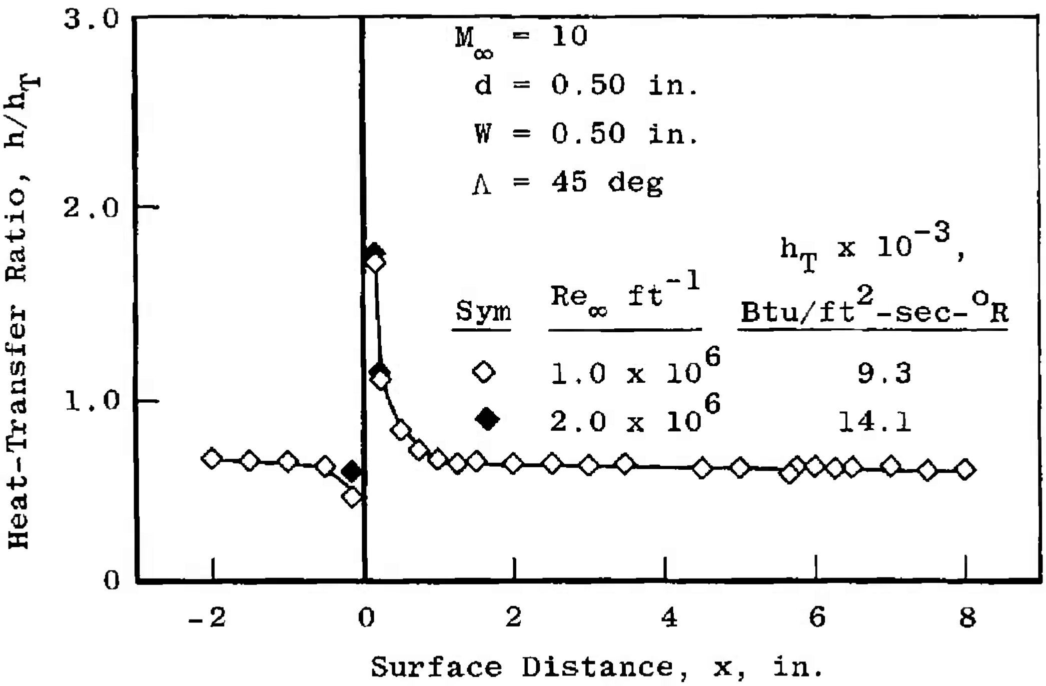


Fig. 6 Effect of Reynolds Number on Leading-Edge Heat-Transfer Distribution at Mach 10

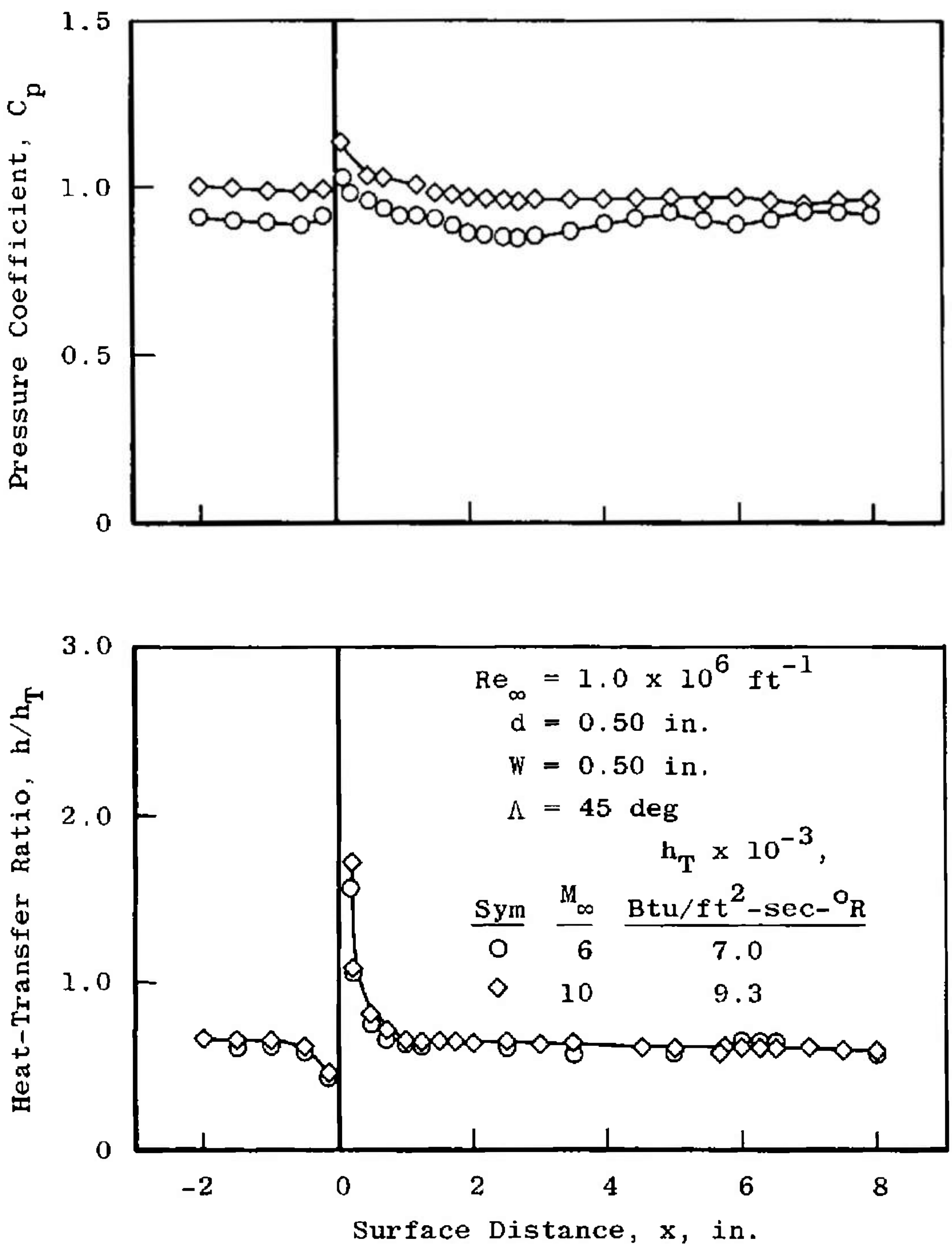


Fig. 7 Effect of Mach Number on Leading-Edge Pressure and Heat-Transfer Distributions

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